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New Concept Power Device; Diamond Vacuum Switch

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Abstract

For the next generation power devices, we have developed several types of unique diamond power devices. By these device performances, we conclude that by using the unique properties of diamond in addition to the superior FOM (figure of merit), the diamond semiconductor has a high potential for the power devices. We introduce new concept power device; diamond vacuum switch and discuss the potential of diamond power devices.

1. Introduction

Among the power device materials, diamond is a most hopeful material from the view point of FOM (figure of merit) due to the highest thermal conductivity, highest breakdown voltage, etc. However, from the difficulties of low resistive material, substrate size, and fabrication process, the power device development using diamond is now behind those of SiC and GaN.

We have realized that diamond has unique properties, such as negative electron affinity (NEA), low-conductive high impurity doping (hopping conduction), and stable exciton states at room temperature, etc. Recently using unique property, namely NEA, of diamond we have developed diamond vacuum switch.

In this talk we introduce the nature of NEA, electron emission PIN diode, and vacuum switch, and discuss the potential of diamond power devices on the basis of the recent results.

2. Diamond unique properties

By the development of the diamond growth technique of microwave plasma CVD, the detailed properties of diamond semiconductor have been clarified. It points out that diamond has unique properties, such as low-conductive high-density impurity doping (hopping conduction), negative electron affinity (NEA) of hydrogen terminated surface and stable exciton states even at room temperature, etc. Using the knowledge about the unique properties of diamond, we have fabricated several types of diamond power devices. In the following sections we introduce the unique diamond power devices; diamond vacuum switch.

3. Negative electron affinity (NEA)

Hydrogen terminated diamond is known as having negative electron affinity (NEA). It means that the vacuum level is energetically lower than the bottom of conduction band. In total photoyield spectroscopy (TPYS) the quantum efficiency of photoelectron emission is measured as a function of photon energy. It shows the absence of any barrier between the conduction-band minimum (CBM) and the vacuum level, i.e., for NEA surfaces, thermalized electrons and excitons dominate the yield and the effective sampling depth is determined by diffusion length of electrons and excitons. Different diffusion length for electrons and excitons have been reported and all exceed a few μm.

Figure 1 shows TPYS results of an undoped (001) diamond film from a fully-hydrogenated (closed circles) and dehydrogenated surface (open circles) measured at room temperature [1]. In case of a fully-hydrogen terminated surface, the threshold energy of the sub-band yield is 4.4 eV, which leads to the negative electron affinity of about –1.1 eV, because the band-gap energy is 5.47 eV. Clearly

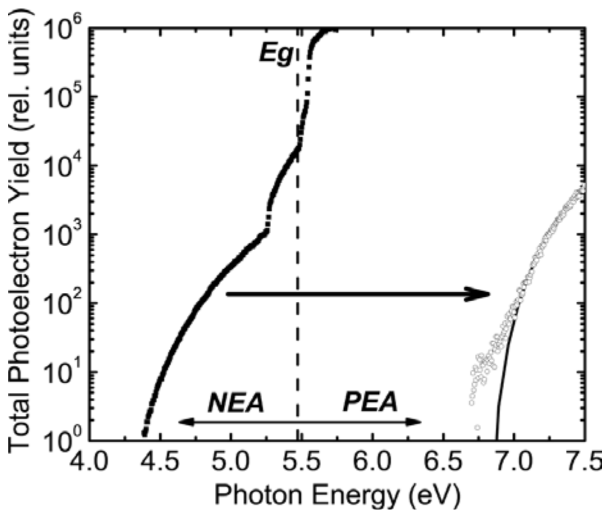

Fig. 1 Total Photo Yield Spectra (TPYS) for hydrogen terminated diamond and dehydro-genated surface. It clearly shows the reversible change between two states.

these measurements shows that hydrogen terminated diamond is NEA. On the other hand, dehydrogenated surface shows electron emission at much higher than band gap. It suggests that dehydrogenated diamond surface has positive electron affinity (PEA).

4. Electron emission PIN diode

From a viewpoint of the electron emitter, in principle, the electrons excited from valence band or injected from outside automatically spill out from the surface with high uniformity, and high emission efficiency. Actually, electron emission from diamond p-n or p-i-n diode with NEA was confirmed. The amount of emission current from diamond p-n diode reached almost 10 % of forward current [2,3].

5. Diamond vacuum switch

We have applied this electron emission diode to the emitter for vacuum switch devices [4.5]. High voltage (E = 10 kV) switching experiments were carried out with a 200 MΩ resistance as a load, as shown in Fig. 2. The V_A was monitored by a high voltage divider. It is a point in this experiment to investigate how low the V_A becomes with maintaining certain I_A. Fig. 3 shows a result of a 10 kV switching during RT operation. In this experiment, diode voltage and diode current are the input signal. When the input power is ON, diamond diode current is turned on, and immediately V_A dropped from almost 10 kV (9.8 kV) to the very low level (160 V). Such ON and OFF switching of 10 kV was obtained without any instabilities. Slow rises of the V_A (or slow drop of the I_A) at off-states was due to the voltage divider including 10 GΩ.

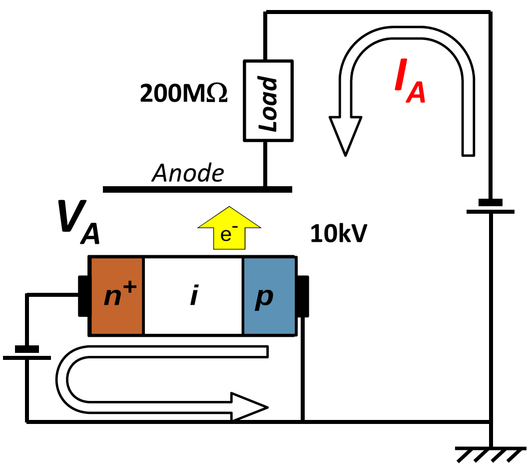

Fig. 2 Vacuum switching device. Diamond PIN diode is used as emitter. High voltage (E = 10 kV) is controlled by the ON/OFF of PIN diode.

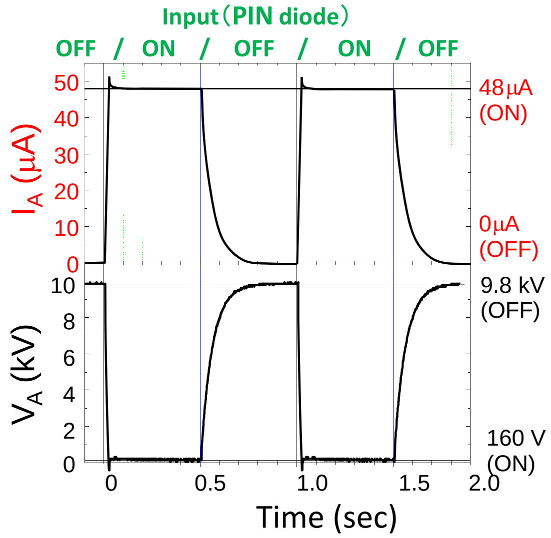

Fig. 3. Time change of IA and VA. They are controlled by the ON/OFF of Diamond PIN diode. 10 kV voltage can be controlled by the small voltage around 10V.

6. Conclusions

We have introduced new types of power devices using unique properties of diamond, specially diamond vacuum switch. It shows that diamond power device has high potential for high voltage region.

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References

[1] D. Takeuchi, C. E. Nebel, and S. Yamasaki, J. Appl. Phys., 99, (2006) 086102.

[2] S. Koizumi, T. One, and T. Sakai, Ext. Abstr. (20th Diamond Symp., 2006); Japan New Diamond Forum, p.221 [in Japnese].

[3] D. Takeuchi, T. Makino, H. Kato, H. Okushi, and S. Yamasaki, Phys. Stat. Sol. A208, (2011) 2073.

[4] D. Takeuchi, S. Koizumi, T. Makino, H. Kato, M. Ogura, H. Okushi, H. Ohashi, S. Yamasaki, IEDM2012 (CA, USA)), IEDM Technical Digest, Vol. 7, No. 6, pp.167 – 170.

[5] D. Takeuchi, T. Makino, H. Kato, M. Ogura, H. Okushi, H. Ohashi, and S. Yamasaki, Jpn. J. Appl. Phys., 51, (2012) 090113.